LANSCE DIVISION RESEARCH REVIEW

Inclusive (n,xn) Double-Differential Cross-Section Measurements

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In calculations of radiation transport with protons and neutrons, it is important to describe processes where one of these nucleons interacts with a nucleus while protons or neutrons are emitted in the reaction. These processes are especially important (although not well known) for incident energies above 20 MeV for programs in accelerator transmutation of waste, radiotherapy, and spallation-neutron-source development. The quantity that describes the probability of emitting a nucleon at a given angle with a given energy is called the double-differential cross section (DDX). For proton-induced reactions, DDX cross sections have been measured for many years. Also there is some information on neutron-induced reactions where protons are emitted in the reaction. But DDX data for neutron-induced reactions where neutrons are emitted are very limited and in fact have never been obtained above 100 MeV. In this research highlight, we describe measurements of inclusive (n,xn) cross sections (i.e., one neutron is detected, but no other reaction product x) for incident-neutron energies ranging from 20 to 400 MeV. The emitted neutrons were detected by the proton-recoil method, using specially designed phoswich detectors (i.e., the phosphor-sandwich technique). Measurements were carried out at the Weapons Neutron Research Facility (WNR) using the time-of-flight (TOF) method. The overall neutron TOF was determined from signals originating from the accelerator proton burst and the phoswich detector. Cross sections thus obtained will be compared to the calculations using the intra-nuclear-cascade-evaporation (INCE) model[1] and the GNASH code.[2]

DDX Data—Needs and Challenges

Intermediate-energy-proton accelerators are used in conceptual accelerator-driven subcritical systems for long-lived nuclear-waste transmutation and in cancer therapy. For these reasons, there is a great deal of interest in cross sections in the intermediate-energy region. To design these facilities, DDX measurements of proton-induced reactions were performed after 1988. These data contributed to improvements to the following codes: the INCE code, quantum-mechanical-molecular dynamics (QMD) associated with the statistical-decay model code,[3] and the quantum-mechanical pre-equilibrium Hauser-Feshbach code.[2] For instance, predictions from recent INCE calculations have greatly improved compared to the original high-energy transport code developed in the early 1970s. Adjustments to parameters, such as the effective nucleon-nucleon-collision cross sections at medium energies, were made in INCE and QMD codes. Adjustments were also made to the V_0 parameters in the Feshbach-Kerman-Koonin (FKK) formalism.[4]

Proton-induced reactions, however, give limited information about reactions at intermediate incident energies. At these energies, protons induce a cascade reaction that starts from an initial *p-n* collision in heavy neutron-rich targets. Neutron-induced reactions can play an important role in gaining a better understanding of the whole cascade process. For FKK calculations, data for neutron-induced reactions are required to determine the value of $V_0(p\text{-}p)/V_0(p\text{-}n)$ at the low-energy end of the intermediate-energy region, but this value has so far only been reported at an incident energy of around 100 MeV.

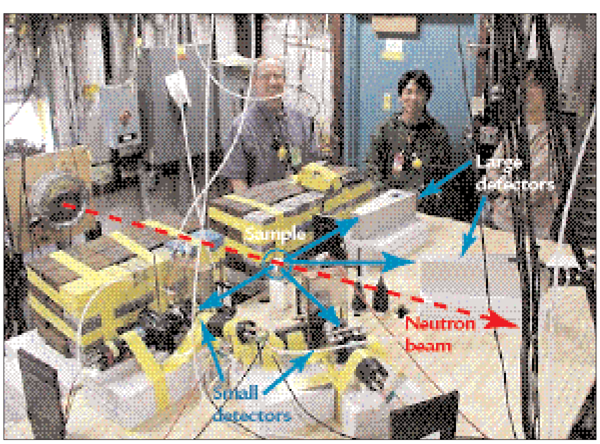
The present state of data suggests that the nuclear-model codes might have trouble predicting DDXs. For example, it is well known that there are relatively important changes in the nuclear-optical potential[5] in the 50- to 300-MeV energy region. The optical-model parameters are important input to the calculations. Secondly, DDX data for proton-induced reactions barely cover this energy range, and therefore they do not constrain the calculations as much as needed. Then there are the thick-target-neutron yields[6] that we measured for incident-proton energies around 1 GeV, and these have some disagreement with the results of the LAHET code[7] in the energy region of several tens of MeV. Thus, even the proton-induced data leave much to be desired in the development of reaction-model codes to predict neutron-induced DDXs.

Measurement of (n,xn) Cross Sections

WNR provides short and intense neutron pulses over a wide continuous-energy range that covers the nuclear-optical-potential changing region. Data at these energies can give information to supplement those for proton-induced reactions for improving the INCE and FKK calculations. These neutron data can thus provide advances in intermediate-energy nuclear physics that can lead to more accurate neutron-transport calculations for nuclear-engineering purposes.

The purpose of this study is to measure inclusive Fe(n,xn) DDX for incident neutrons with energies from 20 to 400 MeV. The measurement necessitated an experimental method having both an acceptable detection efficiency and an energy resolution suited to the continuous-energy neutron beam.

The experiment was performed on flight path (FP) 4FP15L at WNR. The experimental arrangement is shown in Fig. 1. With a continuous-energy-neutron beam, the time between neutron production from the WNR target and the detector signal gives the sum of the flight times for the incident and emitted neutrons. The TOF of the emitted neutrons can be obtained from its energy measured in the detector. The TOF of the incident neutron is obtained by difference. To detect the emitted neutrons, we use the recoil-proton method. Here, neutrons emitted in the reaction knock out protons from a polyethylene disk, commonly called a "radiator." These recoil protons are detected by a combination of a thin detector (plastic or gas) followed by a thick Na(Tl) crystal. In passing through the thin detector, a recoil proton leaves a small part of its energy in the detector, and this signal is used to identify the particle as a proton. The rest of its energy is deposited in the NaI(Tl) detector—unless the proton exits the crystal either because of its initial direction or because it is scattered out of the crystal.



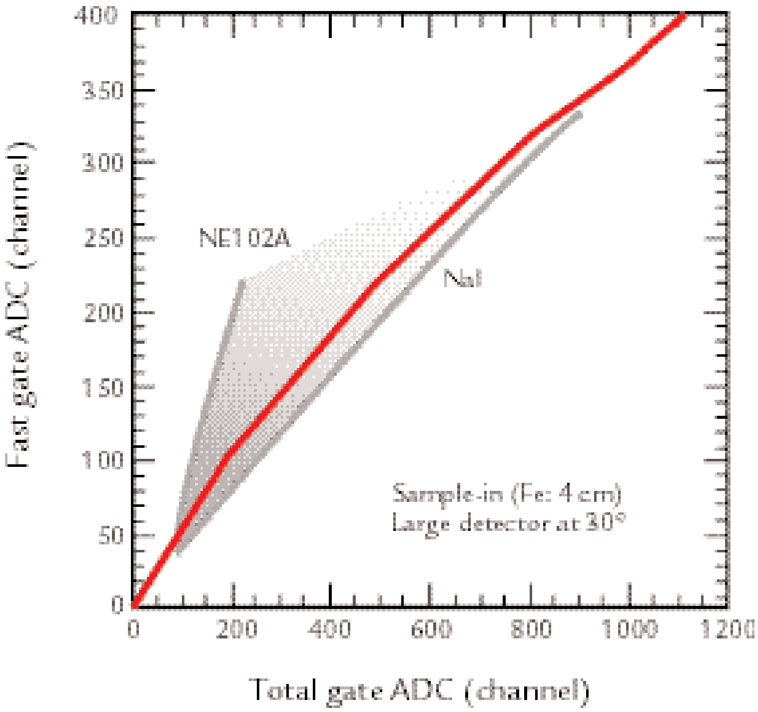
↑ ***Fig. 1.*** *Detector arrangement showing the direction of the incident neutron beam, the Fe sample, and the small and large detectors.*

This experiment employed unique detectors whereby an Na(Tl) crystal was integrated into a package with plastic scintillators on the sides of the crystal but not on the entrance face. One photomultiplier tube viewed the total light from both NaI and plastic scintillators. Because the pulse durations of light from these two types of scintillators are very different, we can tell if the light came from the NaI(Tl) crystal alone, or from the plastic alone, or from both. This combination of two types of scintillators with different pulse durations is called a "phoswich." *Good* events are those in which all of the recoil-proton energy is deposited in the NaI(Tl) crystal. If the recoil proton exits the side of the NaI(Tl) crystal, this is a *bad* event; the plastic scintillator gives a signal used to reject the event. Our phoswich detectors have a detection efficiency considerably higher than that of magnetic spectrometers, which cover a relatively narrow energy range, and these phoswich detectors are better suited for simultaneous multi-angle measurements.

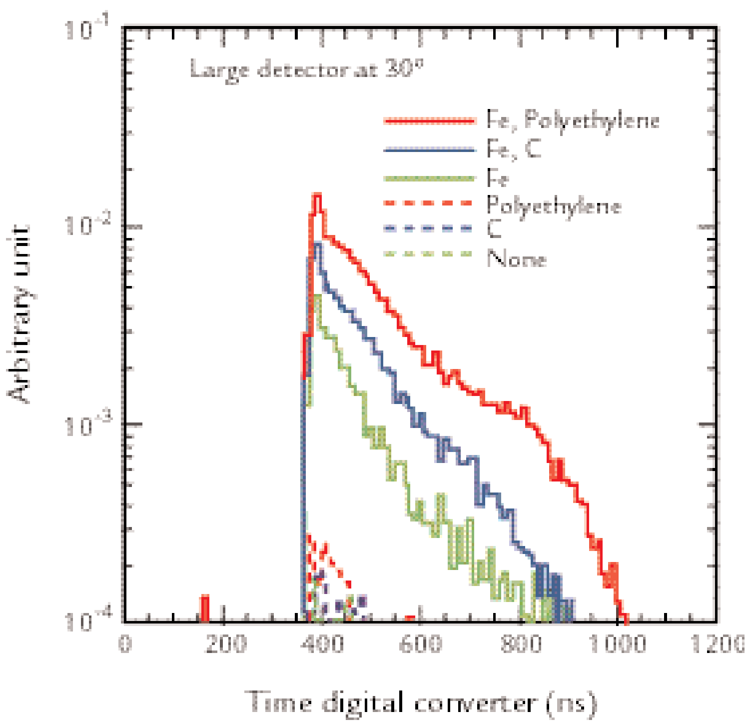
To discriminate full- from partial-energy-deposition events in the NaI crystal, two detectors of different sizes were used with NaI(Tl) crystal lengths of 35 cm and 5 cm. These detectors were equipped with radiators having thicknesses of 20 mm and 4 mm for the large and the small detectors, respectively. The distance between the sample and the phoswich detectors was about 50 cm, and the detection angles were 30° and 90°. To subtract events from carbon in the polyethylene radiator, we also made measurements with dummy carbon disks. The sample was a 4-cm-thick, 5-cm-diam Fe disk. To eliminate charged-particle events from the Fe sample, plastic scintillators were set between the sample and the radiators. A plastic scintillator placed behind the phoswich detector was used to eliminate high-energy recoil protons with a range longer than the length of the detector.

Conclusion

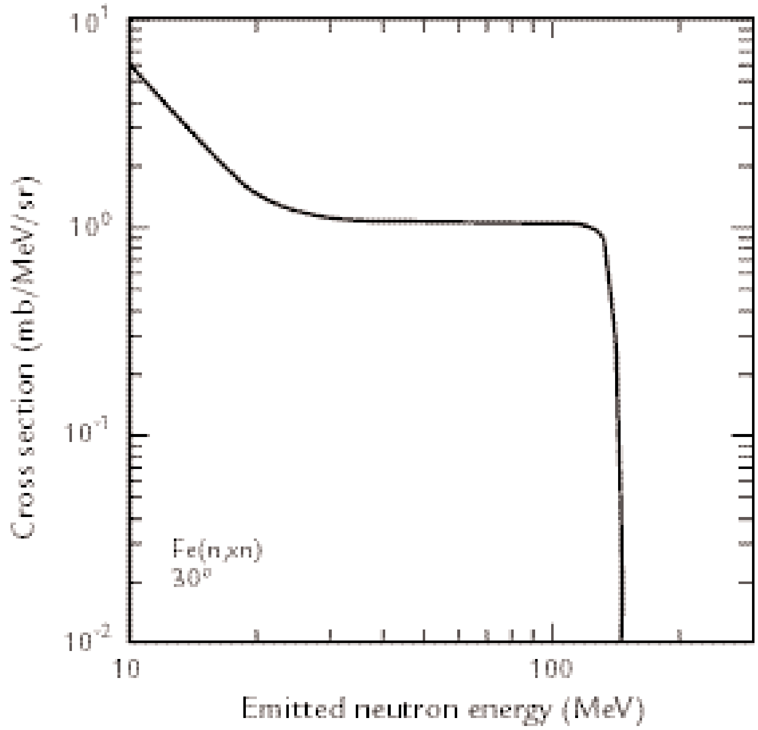
Pulse-shape discrimination of events from the NaI(Tl) region from those in the plastic scintillator was clear for the phoswich detector (Fig. 2). The TOF spectra for the large phoswich detector are plotted in Fig. 3. Event rates without the Fe sample were much less than that with the sample in. Counts using the polyethylene radiator were about twice that from the dummy carbon disk. Fig. 4 shows calculated DDX results, with which we will compare the data we are obtaining in this experiment. This calculation is for only one incident neutron energy, and our WNR data will cover all neutron energies from 20 to 400 MeV.



← *Fig. 2.* *Pulse-shape discrimination for the large phoswich detector. Two gates are placed on the signal: a fast gate and a total gate. Because of the differences in the pulse durations from the NE102A (plastic) scintillator and the NaI scintillator, we can identify those events that interact only in the NaI detector, those that interact only with the NE102A detector, and those that leave part of their energy in each detector (the region between the curves labeled NE102A and NaI). The good events, namely those that leave all of their energy in the NaI detector, are those below the red curve in the figure. (ADC means analog-to-digital converter.)*



← *Fig. 3.* *Neutron TOF spectra for the large phoswich detector. Solid and dashed lines show results of Fe sample-in and -out, respectively. Red, blue, and green lines represent polyethylene radiator data, dummy carbon radiator data, and data with no radiator, respectively.*



↑ ***Fig. 4.*** *Neutron-production DDX as calculated by the GNASH code for one incident neutron energy of 150 MeV. We will test the predictions of this code at this energy and at all energies from 20 to 400 MeV with our experimental data.*

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Nearly 5 years ago, when John Browne became the

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